

# A possible influence of magnetic fields on the rotation of gas in NGC 253

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## ABSTRACT

The magnetic fields that are present in the galaxy NGC 253 are exceptionally strong. This means that they can influence the rotation of matter and hence the mass-to-light ratio. In this context, we address the issue of the presence of a non-baryonic dark matter halo in this galaxy.

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## 1 INTRODUCTION

NGC 253 is a nearby late-type starburst spiral galaxy. Its rotation curve, which has been measured by Puche et al. (1991) and Arnaboldi et al. (1995), increases with radial distance. However, another measurement by (Bland-Hawthorn et al. 1997), supported by (Hlavacek-Larrondo et al. 2011), has indicated that the rotation decreases for larger radii. This fall-off suggests that NGC 253 could be poor in non-baryonic dark matter. We calculate the mass-to-light ratio by treating NGC 253 as a flattened disc-like object, and we find that this ratio is low.

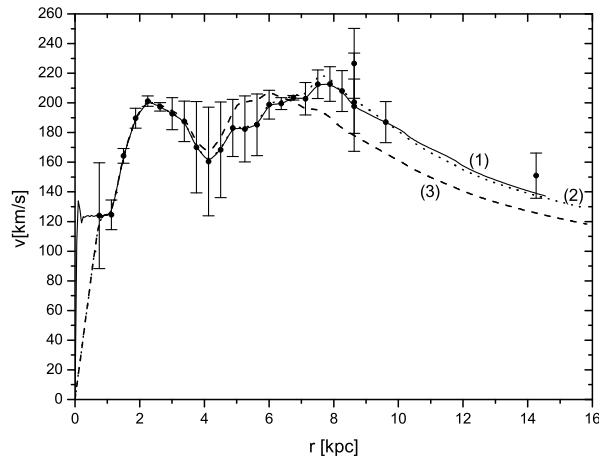
Several examples of other spiral galaxies have been described consistently within the framework of the global disc model, which suggests they could be disc-like objects without a massive non-baryonic dark matter halo (Jałocha et al. 2008, 2010a,b). Moreover, magnetic fields can help to reduce the missing mass problem. As shown by (Battaner et al. 1992; Kutschera & Jałocha 2004; Battaner et al. 2008), magnetic fields can influence the rotation of partially ionized gas. In the disc of NGC 253, there are exceptionally strong magnetic fields present, which reach  $18\mu\text{G}$  (Heesen [I] et al. 2009; Heesen [II] et al. 2009; Heesen et al. 2011; Heesen [III] et al. 2009). These coexist with diffused warm ionized gas, extending out to large radii (Hlavacek-Larrondo et al. 2011). We attempt to estimate the influence of such fields on the rotation and the mass-to-light ratio in this galaxy. Here, we consider only regular (large-scale) fields. Given that small-scale (turbulent) fields are usually at least as strong as the regular field, this (analytically necessary) omission could have a significant effect.

## 2 SURFACE MASS DENSITY AND MASS-TO-LIGHT RATIO

We use the rotation data from (Hlavacek-Larrondo et al. 2011) shown in figure 1. The last measurement point located at  $r_{\text{rot}} = 14.3$  kpc is separated from other rotation data extending out to radius  $r_{\text{cut}} = 9.6$  kpc. For numerical reasons, we treat the points with  $r < r_{\text{cut}}$  as the rotation curve, while the last point at  $r_{\text{rot}}$  serves as a control point. The surface brightness measurements in the K filter extend out to large radii with the outermost point at  $r_K = 11.8$  kpc (Jarrett et al. 2003). Since  $r_K > r_{\text{cut}}$  these measurements can be used to constrain the surface mass density for  $r > r_{\text{cut}}$ .

To find a global surface mass density, both the rotation and the brightness data are needed. For lower radii ( $r < r_{\text{cut}}$ ), the rotation curve is used, while for  $r \in (r_{\text{cut}}, r_K)$  the surface mass density and the surface brightness are assumed to be proportional to each other. In effect, a global rotation curve corresponding to the (still unknown) global surface mass density should agree (within error limits) with the rotation at  $r_{\text{rot}}$ . To meet these requirements, the global surface mass density was found with the help of the iteration method described by (Jałocha et al. 2008). In the current context, this method allows us to obtain a surface mass density that agrees both with the rotation data for  $r < r_{\text{cut}}$  and with the brightness measurements for  $r \in (r_{\text{cut}}, r_K)$  (in the original situation, neutral hydrogen measurements were used for  $r > r_{\text{cut}}$ ).

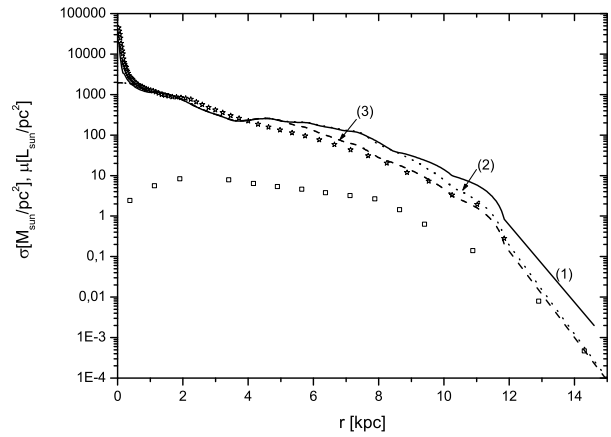
The resulting global surface mass density is shown in Fig.2 and is compared with the surface brightness in the K filter, using the surface density of the neutral hydrogen taken from (Puche et al. 1991). The corresponding (local) mass-to-light ratio as a function of radial distance is shown in Fig.3. This function grows, reaching 3.5, then it stabilizes at  $r = 9.6$  kpc ((this plateau is a result



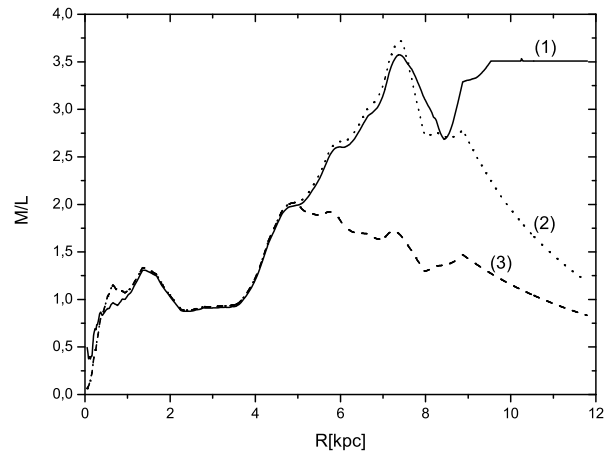
**Figure 1.** Rotation curve of the spiral galaxy NGC 253. The full circles with error bars represent the measurements taken from (Hlavacek-Larrondo et al. 2011). The solid line (labelled 1) denotes the model rotation curve obtained in the global disc model. The dotted line (labelled 2) denotes a small modification of the rotation curve (used in the text to show that a small change in the rotation can greatly influence the mass-to-light ratio). The dashed line (labelled 3) denotes a test rotation curve discussed in the text (the rotation was lowered at larger radii so that the mass-to-light ratio is reduced and decreases with large galactocentric distances).

of the assumption made earlier). Although growing, the mass-to-light ratio is low – the ratio of the total mass to the total brightness is 1.42. Bell & de Jong (2001) stated that, for spiral galaxies, the stellar mass-to-light ratio in near-infrared is normally approximately 2. Therefore, if we obtain results that are, on average, close to this value, we conclude that most of the galaxy mass consists of baryonic matter in the form of stars. In conjunction with the declining rotation curve for large radii, this fact allows us to conclude that the global disc model is a good approximation of the distribution of matter in NGC 253.

An increase in the mass-to-light ratio is usually attributed to the presence of a non-baryonic dark matter halo, which is expected to manifest itself especially for large radii. We show that a surface mass density can be obtained so that the corresponding rotation curve of NGC 253 agrees with measurements within error limits; the surface mass density gives a mass-to-light ratio that decreases for large radii. To show this, the rotation curve (labelled 1 in Fig.1) has been modified slightly, giving rise to the dotted curve labelled 2. Curves 1 and 2 differ only slightly, and both agree with the measurements within error limits. However, this small alternation of the rotation curve results in a significant change in the mass-to-light ratio (see Fig.3, dotted curve 2). It can be seen that the mass-to-light ratio grows reaching 3.75 at  $r \approx 7$ , kpc and then it decreases to  $\approx 1.25$ . This example illustrates that the mass-to-light ratio is very sensitive to modifications in the rotation curve. It shows also that the rotation of the galaxy NGC 253 can be accounted for with a disc-like distribution of matter, without the significant contribution of a spheroidal halo of dark matter. Surely, this does not prove that nonbaryonic dark matter is not present in NGC 253, but rather that, in some instances, its influence might be significantly overestimated.



**Figure 2.** The solid line (labelled 1) shows the surface mass density in the global disc model calculated based on the rotation curve (Hlavacek-Larrondo et al. 2011). The star symbols denote the surface brightness in the K filter (Jarrett et al. 2003). The squares denote the surface density of HI+He based on (Puche et al. 1991), extended by the last three points, so that it converges to the dynamical mass density. The dotted line (labelled 2) denotes the surface mass density calculated based on the rotation curve 2 in Fig.1. The dashed line (labelled 3) denotes the surface mass density calculated based on the rotation curve 3 in Fig.1.



**Figure 3.** The solid line (labelled 1) is the mass-to-light ratio profile. The dotted line (labelled 2) is the change in the mass-to-light ratio caused by a small modification of the rotation velocity. The dashed line (labelled 3) is the mass-to-light ratio profile corresponding to rotation curve 3 in Fig.1.

### 3 MASS-TO-LIGHT RATIO AND MAGNETIC FIELDS

The magnetic fields present in NGC 253 are very strong, reaching  $18\mu\text{G}$ , and they influence the motion of ionized gas. Because the rotation for large radii is measured using emission lines from a diffused ionized gas (Hlavacek-Larrondo et al. 2011), the rotation curve should be corrected for this non-gravitational interaction, so that the dynamical mass can be correctly estimated. This effect can reduce the mass-to-light ratio, and it should be especially prominent for large radii (Kutschera & Jalocha 2004).

To estimate it, first we assume a test rotation curve that agrees with the measurements at small radii (within error limits) and differs from them for radii greater than  $\approx 7$  kpc. The test curve is shown in Fig.1 (dashed curve 3). We assume that the test curve represents the rotation we would expect to measure in the absence of magnetic fields (with the gravitational field unchanged). Similar to (Jafrocha et al. 2012), we can now estimate the magnetic field that is responsible for such a difference in rotation. We begin with the NavierStokes equation

$$(\vec{v} \circ \vec{\nabla}) \vec{v} = -\vec{\nabla} \Phi + \frac{1}{4\pi\rho} (\vec{\nabla} \times \vec{B}) \times \vec{B}. \quad (1)$$

Because we are interested in the rotation in the plane  $z=0$ , we investigate only the radial component of this equation. In the case of axial symmetry, assumed for the simplicity of calculations, the derivatives with respect to  $\phi$  are zero. Then, the radial part of equation (1) reduces to

$$-\frac{(\delta v_\phi)^2}{r} = \frac{1}{4\pi\rho} \left( B_z (\partial_z B_r - \partial_r B_z) - \frac{1}{r} B_\phi \partial_r (r B_\phi) \right).$$

Here,  $(\delta v_\phi)^2$  is the difference in the squares of rotation speed for rotation curves 1 and 3 in Fig.1, entirely due to the magnetic field. In the case that we consider, we assume that without the influence of magnetic fields, the rotation velocity would be smaller, that is  $\delta(v_\phi)^2 = 0$ , whereas with magnetic fields  $\delta(v_\phi)^2 > 0$ .

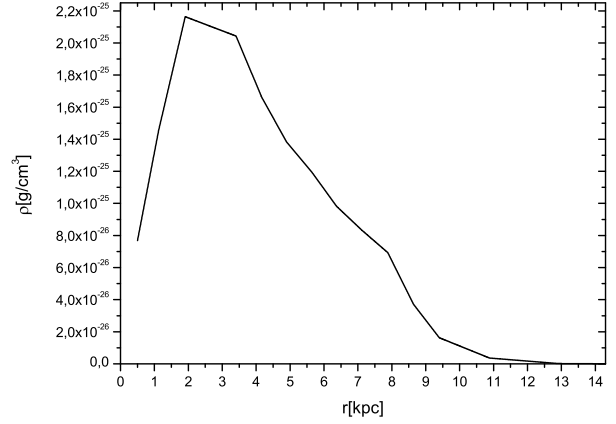
We analyse only the effect of the azimuthal component of the magnetic field. The analysis of just a single component is sufficient to demonstrate, to the order of a magnitude, the possible effect of the influence of the magnetic field. From the symmetry of the field with respect to the plane  $z = 0$ , we can expect the vertical component of the field to vanish on the disc. If so (and from  $\phi$ -independence), the radial component of the field will have had no effect on the rotation curve, because in the radial part of  $(\vec{\nabla} \times \vec{B}) \times \vec{B}$  the term containing the radial component of the magnetic field is multiplied by the vertical component. Then, equation (1) reduces to  $(\delta v_\phi)^2 = \frac{1}{4\pi\rho} B_\phi \frac{\partial}{\partial r} (r B_\phi)$  with the solution

$$B_\phi(r) = \frac{1}{r} \sqrt{(r_1)^2 (B_\phi(r_1))^2 + 8\pi \int_{r_1}^r \varrho(r) (\delta v_\phi(\xi))^2 \xi d\xi}. \quad (2)$$

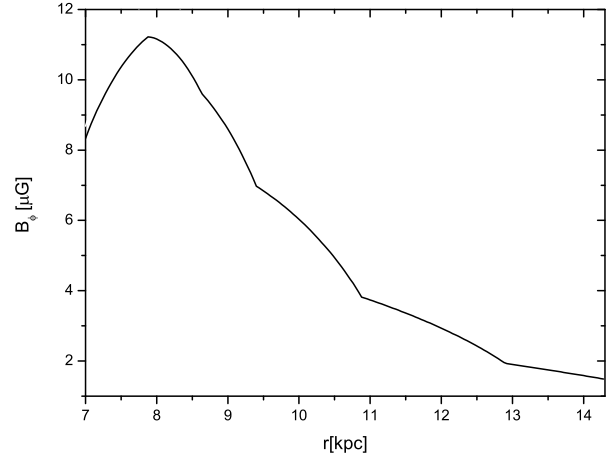
To find particular solutions, we assume that  $\rho$  decreases exponentially with the altitude above the mid-plane and that its column density is identical to the surface density of neutral hydrogen from (Puche et al. 1991), see Fig.4. These measurements are available at radii smaller than those for the rotation. To overcome this difficulty, we have extended the column density so that the joint surface density of neutral hydrogen and helium agrees for larger radii with the surface mass density obtained based on rotation curve 3. The numerical solution to equations 2 is shown in fig.5.

The solid line represents the azimuthal magnetic field required for the assumed difference between rotation curves 1 and 3 shown in Fig.1. The required field is no greater than  $11.25\mu\text{G}$ . For small radii, the field magnitude is larger; for larger radii, it decreases with the radius.

The magnitude of the magnetic field in NGC 253 is of the order of  $7 - 18\mu\text{G}$  (Heesen [I] et al. 2009; Heesen et al. 2005). It is strongest in the central part of this galaxy, and it decreases in the outer parts. At the radius of  $\approx 9\text{kpc}$ , we note that the magnetic field is  $\approx 10\mu\text{G}$  (Heesen et al. 2005). We conclude that the magnetic field in NGC 253 is sufficient to increase the rotation to the degree assumed above. This change in the rotation diminishes the galaxy



**Figure 4.** Bulk density of HI in the disk plane obtained from the surface density taken from (Puche et al. 1991)



**Figure 5.** Azimuthal magnetic field needed to change the rotation so that the profile of the mass-to-light ratio is smaller and decreases with the large galactic radius.

mass by 18% from  $5.68 \times 10^{10} M_\odot$  (the mass in disk model for rotation curve 1 inside  $r < 14.3$  kpc, the same value as for curve 2) to  $4.82 \times 10^{10} M_\odot$  (for the rotation curve 3). The mass-to-light ratio was calculated based on the rotation curve 3, and it is shown in Fig.3 as the dashed curve 3. The mass-to-light ratio has decreased significantly; it reaches the maximal value of 2 and decreases for  $r > 5$  kpc. When accounting for the possible effect of the magnetic field, the relative change that results for the estimated galaxy mass is not large; however, the influence of the field significantly changes the value and the behaviour of the mass-to-light ratio for radii greater than 5 kpc.

Of course, the situation that we consider is simplified. In NGC 253, there is also a small-scale turbulent field besides the regular, large-scale magnetic field, and there are also other phenomena that influence the magnetic field, such as gas flows out of the disc plane or interactions with the radio halo. This makes the real configuration of the magnetic field much more complex than in the case we

investigate. However, even such an idealized, simplified situation allows us to demonstrate that the magnetic fields can influence the motion of matter, and hence the rotation curve of a spiral galaxy.

#### 4 SUMMARY

The latest measurements show that the rotation curve of NGC 253 decreases for large radii, which makes this galaxy a natural candidate for a disc-like galaxy without (or with only a small fraction of) non-baryonic dark matter. Indeed, the mass distribution can be consistently described in the global disc model, without introducing any massive spherical component. The resulting mass-to-light ratio (in the K filter) is low. In addition, this ratio can be reduced further by the very strong magnetic field present in NGC 253, which should influence the motion of ionized gas. Recall that the mass-to-light ratio was too high in the maximal disc model of NGC 253 when the surface brightness in the B filter was used (Hlavacek-Larrondo et al. 2011). Moreover, in contrast to Hlavacek-Larrondo et al. (2011), we do not assume in advance that this ratio is a constant. In our approach, the mass-to-light ratio is a local quantity, a function of the radius.

With the rising rotation curve of Puche et al. (1991) the mass-to-light ratio increases, reaching 4 in the region where the measurements of rotation are available. When the possible influence of magnetic fields is taken into account, the ratio is reduced, reaching the maximal value of 2.25. The required field decreases with the radius, starting from  $11.5\mu\text{G}$ . With this field, the mass-to-light ratio increases with the radius, and thus it is reduced differently than in the case with the decreasing rotation curve.

The fall-off in the rotation curve for large radii suggests that NGC 253 is a disc-like object, without a significant amount of non-baryonic dark matter. However, even the analysis based on the increasing rotation curve has given a low mass-to-light ratio. Additionally, this ratio is reduced when the possible influence of the magnetic field is taken into account. Recall that in calculating the mass-to-light ratio, the surface mass density of gas was not subtracted from the total surface mass density, because the measurement of neutral hydrogen ended earlier than the measurements of surface brightness and of rotation. Therefore, in this work we have obtained an upper bound for the mass-to-light ratio (there are other mass components apart from stars that contribute to the surface mass density).

Our analyses of NGC 253, as well as a previous analysis of NGC 891, show that values of the mass-to-light ratio calculated in the disc model, especially for large radii, are very sensitive to even small changes in the rotation curve, and they might also be influenced by other factors, such as the magnetic field, which have not yet been taken into account. Using estimates of the order of a magnitude, essentially, we have shown that a large-scale field of about the observed strength can influence the rotation curve. In certain galaxies, this might significantly affect deductions on the size of the dark matter halo, which are based on the rotation curve. Therefore, we should be cautious in drawing conclusions about the dark matter abundance in spiral galaxies from the increase in their mass-to-light ratio, if we do not know and cannot account for the various factors that can influence this ratio.

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